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Simulation of Surface Ship Dynamics Using Unsteady RANS Codes

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Abstract

This paper presents progress in a three-year Challenge Project, begun in 2001 and led by the Office of Naval Research (ONR), with the objective of demonstrating a capability to simulate time-dependent six-degree-of-freedom (6-DOF) motions of ships in waves and the associated near-field flow using unsteady Reynolds-Averaged Navier-Stokes (RANS) codes. Challenge Projects are sponsored by the U.S. Department of Defense's (DoD) High Performance Computing Modernization Program (HPCMP) Office. Two unsteady RANS codes are used in a progression of building-block simulations at both model and full scale and for practical configurations including detailed resolution of propulsors and appendages. The RANS codes are UNCLE, developed at the Mississippi State University (MSU), and CFDSHIP-IOWA, developed at the University of Iowa. The team members for this project are K.-H. Kim (ONR, team leader), R. Miller and J. Gorski (Naval Surface Warfare Center, Carderock Division), R. Wilson and F. Stern (University of Iowa), L. Taylor (MSU), and M. Hyman (Naval Surface Warfare Center, Coastal Systems Station). Computations are presented for increasingly complex bodies. Bilge-keel forces on a three-dimensional rolling cylinder were accurately predicted. Detailed flow and force characteristics were calculated for an unappended naval combatant hull in prescribed pitch and heave. Initial calculations for a fully appended combatant hull gave good qualitative predictions for surface pressure and free-surface elevation. Calculations for a rudder-induced turn led to evaluation of improved methods for representing a free surface.

Introduction

The traditional U.S. naval ship design methodology of repeatedly building and testing various hullforms for surface combatants is rapidly being changed by successful implementation of advanced computational tools and by availability of massive computational resources primarily through U.S. DoD HPCMP. Future surface ship designs will undoubtedly rely more heavily on computations than in the past. The new process will enable a variety of design decisions and trade-offs based on computations. Furthermore, naval ships of the future will be radically different from those currently in the fleet, in order to meet emerging requirements and to accommodate emerging technologies such as electric drive as the main propulsion system. A preceding Challenge Project (1996-2000) entitled "Time-Domain Computational Ship Hydrodynamics" [1], and the more recent "ONR Surface Combatant Accelerated Hydrodynamics S&T Initiative" (1999-2000), made a significant contribution to establishing this new surface ship design paradigm.

The current Challenge Project begun in 2001 is focusing on demonstrating the capability of simulating 6-DOF maneuvering and seakeeping of full-scale ships using unsteady RANS codes. The first year's efforts were summarized in [2]. The technical challenge is to predict the high-Reynolds number turbulent flows to adequately simulate the interaction of large-scale waves and motions of the ship with small-scale turbulence

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and associated forces and moments. One of the major stumbling blocks has been an inadequate capability for computing the nonlinear turbulent free-surface flow about a hull. A major first step was made under the previous Challenge Project where state-of-the-art unsteady RANS methods were used to simulate flow characteristics around an unappended U.S. Navy combatant, DDG-51 hull in regular head waves. Those accomplishments paved the way for prediction of 6-DOF motions of a fully appended ship in a seaway. In this current Challenge Project, two unsteady RANS methods will be applied to simulate time-dependent 6-DOF motions of surface ship in waves, with particular emphasis on roll motion. The two RANS codes to be used are UNCLE, developed at the Computational Simulation and Design Center (SimCenter), Mississippi State University and CFDSHIP-IOWA, developed at the Iowa Institute of Hydraulic Research, University of Iowa.

This effort will perform increasingly demanding simulations of propelled surface ship motion, progressing from model to full scale. The ship hullform chosen for the computations is a conventional transom-stern U.S. Navy destroyer (DDG-51) and its scale model (1/24.8-scale Model 5415), including propeller shafts, support struts, rudders and rotating propellers. A tiered approach is being pursued in which high-fidelity calculations are performed on simpler geometries, for comparisons with experimental data at model scale, in conjunction with highly sophisticated complete-geometry simulations up to full scale.

In this paper, computational results are presented that include prediction of roll motion of a simple three-dimensional cylinder with bilge keels; comparison of the predictions with experimental measurements in a circulating water channel; computations of coupled pitch and heave motions of Mode 5415; and computations of flow around fully appended Model 5415 in straight-ahead motion and rudder-induced maneuver in the horizontal plane.

Future computations will demonstrate the capability to simulate 6-DOF ship motions, maneuvers, and near-field wake, including propeller and viscous effects. The predictions will be one of the first-ever such calculations, which include detailed modeling of the viscous effects on complex interaction of pitch, heave, and roll motions. The product of this research will provide a simulation-based design environment for Navy surface ship hull design, including surface-combatant and other future hullforms.

The study seeks to develop a validated predictive capability for the influence of viscous effects on ship motion for use in conjunction with existing design tools, and to perform large-scale detailed predictions for selected cases identified as critical or of high importance in the design-iteration process. It will introduce the most advanced tools into acquisition and fleet applications. In particular, scalable parallel computing is greatly advancing the complexity of problems for which analysis and design based on large-scale complex flow simulations are becoming feasible.

Computational Tools

The SimCenter at Mississippi State University has developed scalable flow simulation software for both multiblock *structured* grids having arbitrary block connectivity [3] and for multi-element *unstructured* grids [4], known as UNCLE and U^{2}NCLE, respectively. The current parallel algorithm in UNCLE and U^{2}NCLE combines multiple-iteration implicit schemes, characteristic-based finite-volume spatial approximations, and numerical flux linearizations with Block-Jacobi Gauss-Seidel relaxation for the innermost iteration to provide scalable concurrency [5]. Nonlinear free surface [6], general grid motion [7] and moving control surface [8] capabilities have also been incorporated into this algorithm. All tetrahedral and multi-element meshes have been generated with an advancing normal methodology for the boundary layer elements, and with an advancing front/local reconnection (AFLR) methodology for the isotropic elements as given in [9]. This procedure allows generation of high-quality unstructured grids suitable for simulation of high Reynolds number viscous flows with sublayer resolution. All geometry preparation and surface grid generation is performed using SolidMesh [10] with AFLR surface grid generation [11].

The University of Iowa has developed an unsteady RANS code, CFDSHIP-IOWA, for general ship hydrodynamic problems, including resistance, motion, and propulsor. It is a general-purpose parallel code that solves the unsteady RANS equations in either time-accurate or steady-flow mode [12]. The code is written in Fortran 90/95 and has been designed with a modular open-source architecture that supports model

development from outside users without detailed knowledge of data structure and procedures for processor communication required for parallel computing. Version 3.03 is based on a structured multiblock grid approach utilizing higher-order finite difference discretization with collocated flow variables and a pressure-implicit splitting of operators (PISO) algorithm for velocity-pressure coupling. The free surface is modeled using a free-surface tracking algorithm where a two-dimensional kinematic free-surface boundary condition is solved for the wave elevation and the computational grid is dynamically conformed to the hull and predicted free surface at each time step. The surface-tracking approach becomes problematic for free-surface flows with large wave steepness and/or large differences between the unconformed and conformed grid. Such problems could potentially arise for simulation of ships with moderate to large motions. In an effort to increase robustness for such simulations, a fixed-grid approach based on the level-set technique has recently been implemented and tested for simulation of steady free-surface flow around the Wigley and Series 60 ship geometries.

The CFDSHIP-IOWA data structure allows the code to be compiled and executed on either serial or parallel platforms and provides a high level of portability. Large-scale parallel computing is achieved using a multi-level approach where the Message Passing Interface (MPI) is used to distribute computational blocks onto separate processors in coarse-grain mode and OpenMP is used for fine grain loop-level parallelism. This algorithm permits load balancing by allocating threads based on relative block size. The code was extended to allow prescribed and predicted 6-DOF ship motions with incident waves. Chimera overset gridding capability was added recently. This new capability was successfully implemented in the code using Pegasus 5.1 software - developed at NASA Ames through the DoD HPCMO Common High Performance Computing Software Initiative (CHSSI) program - as a pre-processor which automatically creates hole boundaries from boundary condition data and interpolation coefficients for setting boundary values at overlapping block interfaces. The new capabilities will enhance the robustness, fidelity, and efficiency of the current structured-grid approach for applications with fully-appended surface ship configurations with motions.

Viscous Roll Motion of a 3-D Cylinder with Bilge Keels

Roll motion limits ship operability, affects crew performance and ship habitability, and affects dynamic stability and ship capsize. Viscous roll-damping prediction is one of the critical but difficult parts of the motion prediction process. Consequently, current ship-motion prediction methods, mostly potential-flow methods, account for roll effects based on empirical databases obtained primarily from model-scale tests [13]. An initial focus of this project is computation of roll motions for validation of the codes. Using two simple three-dimensional cylinders with bilge keels undergoing a forced roll motion, the accuracy of RANS codes is being determined by comparing the predictions with experimental data for the flow field around the bilge keel and the resulting forces.

The roll motion of a ship is largely influenced by viscous effects. Bilge keels significantly increase the damping of roll motions as well as generate a lift force if any forward motion of the ship is present. Predicting roll effects analytically has been difficult because of the significant viscous effects, even with bilge keels present. As demonstrated by Sarpkaya and O'Keefe [14] bilge-keel damping is a result of the vortices shed from the edge of the keel; damping coefficients from flat plate tests in a free stream are not necessarily accurate for wall-bounded bilge keels. Consequently, roll effects have largely been included in flow predictions empirically, requiring numerous model-scale tests to define coefficients that describe the roll motion. Model-scale coefficients do not necessarily relate well to full-scale behavior due to the differences in Reynolds number. Few viscous computations of roll motions have been reported in the recent past. Yeung, et al. [15] recently presented two-dimensional computational results. The current effort simulates roll motions of a 3-D cylinder with bilge keels. These calculations will provide an indication of the accuracy that can be obtained with RANS codes for predicting viscous roll damping. Such predictions are vital to accurately predicting the seakeeping and maneuvering characteristics of surface ships.

Experiments were recently carried out in the Circulating Water Channel at NSWC, Carderock Division using 3-D cylinders with bilge keels (see Figure 1). That water channel has a 6.7 m (22 ft)-wide and 9.1 m (30 ft)-long square test section with a free surface. Four cylinder/bilge keel configurations were tested, including a

19-inch diameter cylinder with 1 and 2 inch-wide bilge keels and a 35 inch-diameter cylinder with 2 and 4 inch-wide bilge keels. Measurements were made with the models fully and partially submerged in calm water and circulating water simulating forward speed. The cylinders were 13 feet long with an elliptical nose; forces were measured over a 2-foot section of the keels as roll motions were imposed at different frequencies and amplitudes. Forces and pressures were measured on the cylinder. The vortical flow field, including the vortices shedding from the bilge keels, was measured using a Particle Image Velocimetry (PIV) system attached to the rolling cylinder.

Computations were made using the structured UNCLE code. The roll cycle was divided into 360 time steps. Six subiterations per time step were used in most of the calculations. The calculations were performed using 84 processors on Maui's IBM-SP3 computer. The solution for 10 cycles of roll motion took approximately 24 hours with 6 subiterations per time step. Forces on the bilge keels and pressures on the cylinder were computed at every time step. Velocity and vorticity at selected axial locations were also computed at each time step. A fully 3-D structured computational domain consisting of 3 million grid points was created using GRIDGEN, with y+ of 1 for the point closest to the wall. The computational domain extended one body length forward and to the sides, and two body lengths downstream of the body. It was divided into 84 equally sized (33x33x33) blocks for parallel processing.

Initial computations were made for the partially submerged cylinder (35-inch diameter with 2-inch wide bilge keel) undergoing a prescribed roll motion in a steady onset flow at 2 knots, assuming a pure sinusoidal roll motion. The computations were made with a zero Froude number approximation for the free-surface boundary condition using the assumed sinusoidal roll angle as input. Figure 2 shows the computed axial velocity contours. Growth of contours due to convected and locally created vorticity can be seen along the bilge keels. Figure 3 compares the forces on the bilge keel as a function of time. The agreement is qualitatively good. The measured force showed large fluctuations during one cycle of motion. Detailed examination of the measured roll motion revealed that the motion was not smooth and sinusoidal, but fluctuating due to a non-smooth rolling motion of the body caused by the chain drive mechanism that rotates the cylinder.

New computations were subsequently made using the actual, non-smooth angular velocity as input to the RANS solver to account for the actual cylinder motion. Figures 4 and 5 show the comparison of the predicted and measured forces on the bilge keel, with and without forward speed, respectively. The computations are in excellent agreement with the measurements. The computations were able to capture the measured force fluctuations caused by non-smooth angular velocity of the cylinder.

Pitch and Heave Motions of Unappended Model 5415

The problem of prediction of unsteady surface ship hydrodynamics with general 6-DOF motions and incident waves is being investigated using a building block approach in which simulations with either horizontal or vertical plane motions are performed separately before more-complex coupled motions are investigated. Simulations performed in the first year (2001) of the project employed Model 5415 undergoing horizontal plane motions with uniform forward speed and prescribed sinusoidal roll motion [2]. The results showed that the rolling motion resulted in unsteady asymmetric axial velocity contours and a serpentine motion of the vortices emanating from the sonar dome.

Recently, vertical-plane motions were investigated for Model 5415 with combined pitch and heave motions using the CFDSHIP-IOWA code. The simulations were performed for the unappended Model 5415 with double-body geometry at $Re=12\times10^6$. A 16-block structured grid system with 894,504 total grid points was utilized for the simulation that required 16 processors and 525 total CPU hours on the SGI Origin 3000 at Army Research Laboratory in Aberdeen, Maryland. Figure 6 shows the time history of the prescribed heave distance and pitch angle normalized by maximum heave amplitude $A_H=0.01L$ and pitch angle $A_P=5$ degrees, respectively. Time t is non-dimensionalized with a time scale T defined by $T=L/U$ where L and U are the ship length and forward speed, respectively. The period of the prescribed sinusoidal motions was specified as $0.5T$. The prescribed motions modeled a surface ship that is free to pitch and heave while encountering incident head waves. A converged steady-state solution for Model 5415 with uniform forward speed restrained from motions

was used as an initial condition for the unsteady simulation. During the first period and a half ($0 < t/T < 0.75$), the amplitudes of the sinusoidal pitch and heave motions were gradually increased to their maximum values. The resulting solution underwent a transient response for the first two periods after which the transient died out and a periodic response was achieved for $t > T$. Results are shown for one typical period of the periodic response, $1 < t/T < 1.5$.

Figure 7 shows a time sequence of axial velocity contours at every quarter period. For t=1.125T (Figure 7a), the ship was pitching counterclockwise (bow up) at zero pitch angle, so that the boundary layer thickness was reduced along the afterbody while flow separates under the sonar dome due to its upward vertical motion. One-half period later at t=1.375T (Figure 7c), the ship was pitching clockwise (bow down) at zero pitch angle, resulting in a dramatic thickening of the boundary layer and the initial development of a pair of outboard rotating vortices along the afterbody. The downward vertical motion of the bow resulted in the formation of a wake above the sonar dome. At t=1.5T (Figure 7d), the ship reached maximum negative pitch angle and the upward vertical motion of the stern resulted in strengthening of the afterbody vortices.

The time history of the total axial force (C_T) and pitch moment (M_T) is shown in Figure 8 along with frictional (F) and pressure (P) contributions. The response of the axial force was mainly second-harmonic, while that of the pitch moment was purely first-harmonic.

Maneuvering Simulation of Fully Appended Model 5415

Computations of the nonlinear turbulent free-surface flow about a ship hull, particularly at full scale, are extremely demanding. Small-scale appendages and other geometric details such as control surfaces, rotating propulsors, propeller shafts, struts and bilge keels are important for roll-damping predictions. As complexity increases, it gets increasingly difficult to generate good structured grids, and unstructured grids become more attractive. For the present computations using the unstructured U^{2}NCLE code, the geometry of the fully appended Model 5415 was discretized with a high-resolution multi-element unstructured grid, with viscous sublayer resolution on all components. Extensive experimental data for the unappended Model 5415 has been reported [16], and recently experimental data was presented for a rather complete configuration, including rudders, propeller shafts, support struts, and propellers [17].

A free-surface capability was demonstrated during the first year of this Challenge Project [2]. First-ever nonlinear free-surface simulations with a surface-tracking approach for fully appended Model 5415 with rudders, propeller shafts, support struts and rotating propellers were performed at model-scale Reynolds number for steady ahead motion in calm water using the unstructured U^{2}NCLE code. The unstructured mesh used consisted of over 5.7 million nodes, with over 7.7 million prisms and 9.6 million tetrahedra. The flow conditions were Re = 12.02 x 10^6 and Fr = 0.28, an especially difficult condition due to the partially wetted transom stern. The propeller rotation was outboard over the top at 436 RPM. The surface-pressure distribution and the free-surface elevation are shown in Figure 9. The surface pressures indicate the complexity of the flow field, and the expected trends are apparent on the struts, shafts, rudders, and hull. In addition, the effect of the propeller wash on the rudders is apparent from the rather strong low-pressure region on the outboard side of the rudder and a relatively benign pressure distribution on the inboard side. Comparison of experimental [16] and computational results for the free-surface elevation immediately aft of the stern is also shown in Figure 9. Qualitative agreement with the experimental data is good overall, including the maximum free-surface elevation. It should be noted that the computed results are shown at a particular instant of time and the experiments showed the flow in this region to be quite unsteady. The solution for this full-configuration Model 5415 was run with 1440 time steps per propeller revolution. Each propeller revolution required 48 hours on 75 IBM-SP3/512Mb processors (3600 processor hours).

A maneuver was initiated by a rudder deflection for the same configuration and grid, initially with zero Froude number, i.e. a rigid free-surface condition. That essentially reduced the simulation to a 3-DOF maneuver. Using the solution in Figure 9 as an initial condition, a maneuver was initiated by rotating the rudders, leading edge to port, at a rate of approximately 11 degrees per second. Surface-pressure distribution as well as axial velocity distribution in the cutting planes are shown in Figure 10 for the initial stages of this

maneuver. The rudders had deflected approximately 6 degrees at that point and the asymmetry in the pressure distributions on the port and starboard rudders is evident. Axial velocity is displayed on a vertical cutting plane through the center of the propeller shaft in the upper left-hand corner of this figure. Axial velocity is also shown on a horizontal cutting plane through the propellers and rudders in the lower right-hand corner of Figure 10. The asymmetry in the axial velocity contours due to the movement of the rudders is clearly shown.

A rudder-induced maneuvering simulation with a non-rigid free-surface condition encountered difficulties associated with free-surface robustness. Improvements in the free-surface robustness are currently being pursued in two ways. One entails modifications to the free-surface fitting (or tracking/conforming) approach used in Figure 9, and the other is a surface-capturing approach in which the free surface is not fit, but is captured within a region of thickness of a few grid points. These two approaches have now been demonstrated and validated for a Wigley hull in straight-ahead motion, as shown in Figure 11. The predicted free-surface elevations along the hull using the surface-tracking and -capturing methods are compared with the experimental data. The agreement is good. This surface-capturing technique appears very promising in terms of robustness. Using this technique, the flow around the unappended Model 5415 in ahead motion was also computed and is shown in Figure 12. Figure 13 compares the wave elevation along the Model 5415 hull for different methods. The surface-capturing technique performs as well as the previous surface-tracking technique. Improvement and validation of a robust free-surface-capturing technique is currently being done for the maneuvering simulations. Future simulations will be undertaken for maneuvering with the nonlinear free-surface capturing technique.

Summary and Future Efforts

Computations are presented for increasingly complex bodies. Bilge-keel forces on a three-dimensional rolling cylinder were accurately predicted. Detailed flow and force characteristics were calculated for an unappended naval combatant hull in prescribed pitch and heave motions. Initial calculations for a fully appended combatant hull gave good qualitative predictions for surface pressure and free-surface elevation. Calculations for a rudder-induced turn led to evaluation of improved methods for representing a free surface. A surface-capturing technique appears very promising in terms of robustness.

A rudder-induced maneuver with the surface-capturing method will be computed for the fully appended Model 5415. Integration of the computed viscous stresses and pressure distribution on this configuration will provide the hydrodynamic forces and moments acting on the ship. Integration of the 6-DOF equations using these forces and moments will yield the time evolution of the ship's velocity and rotation rate. The sensitivity of the computed trajectory with respect to the free surface will also be examined by comparing this maneuvering solution to the one obtained at Fr=0.

Future efforts will also include unsteady simulations of Model 5415 in incident waves with both forced and free roll motions. Initial free roll simulations will include prediction of roll decay after the model is released from some initial angular displacement at t=0 and will allow for comparison with experimental measurements to be performed at University of Iowa. Planned simulations for Model 5415 with forced and free roll motions will be considerably more complex and computationally demanding.

Acknowledgement

The author is grateful to the Challenge Project team members who are constantly pushing the envelope of computational capability to solve the most challenging Navy problems.

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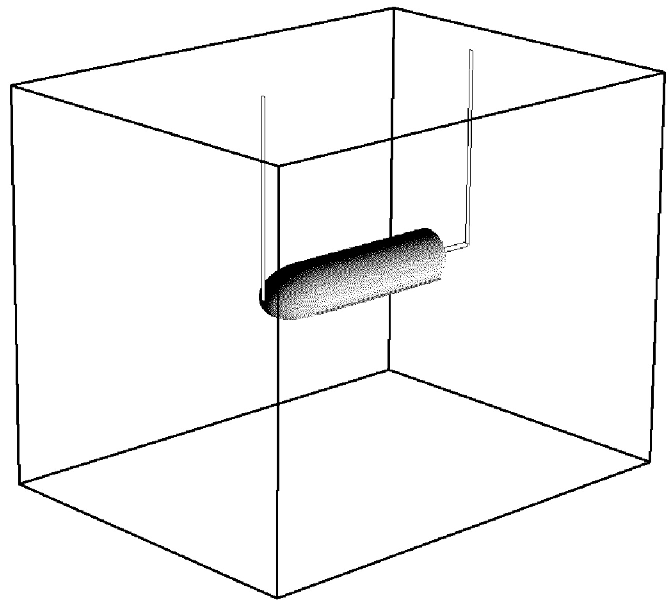

Figure 1. Experimental Setup for Roll Experiments in the Circulating Water Channel

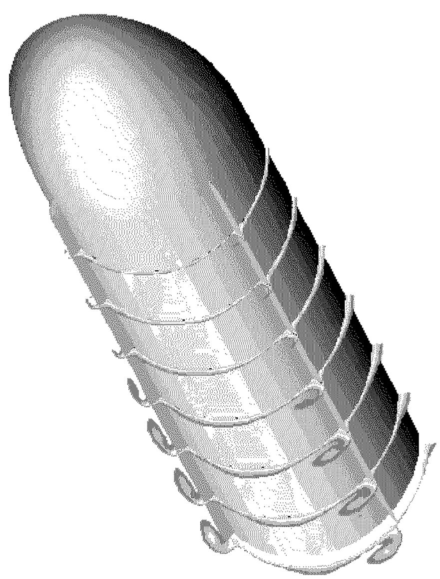

Figure 2. Axial Velocity Contours – Partially Submerged Cylinder (D=35 in.)
(f = 0.32 Hz, Amp = 15 deg, Fwd Speed = 2.0 knots)

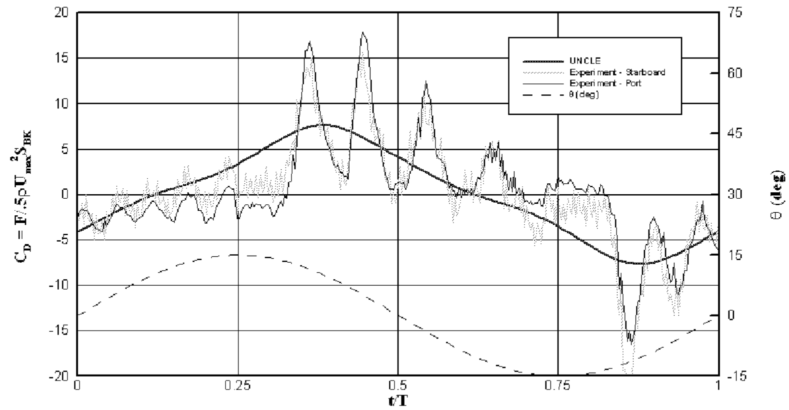

Figure 3. Force on Bilge Keel - Submerged Body (f = 0.32 Hz, Amp = 15 deg, Fwd Speed = 0 knots)

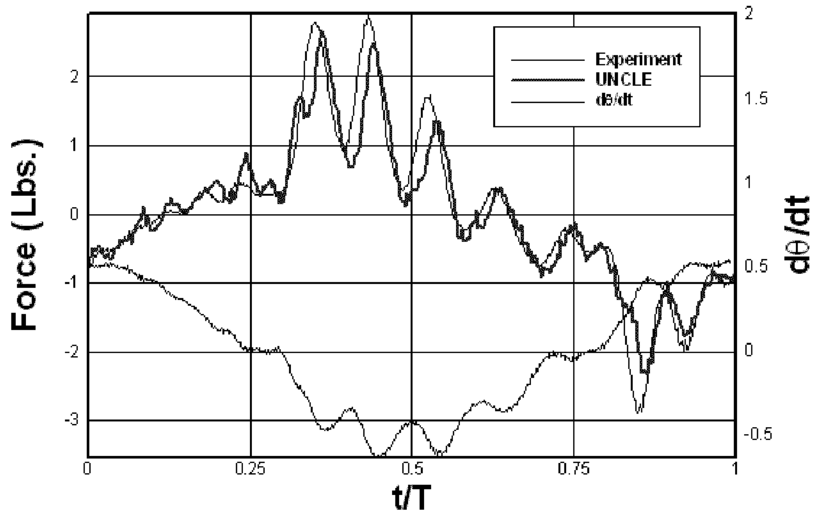

Figure 4. Force on Bilge Keel - Submerged Body (f = 0.32 Hz, Amp = 15 deg, Fwd Speed = 0 knots)

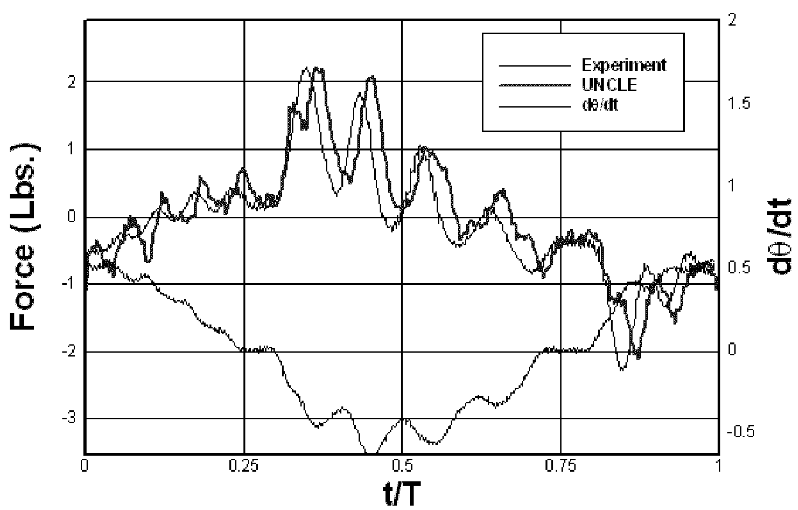

Figure 5. Force on Bilge Keel - Submerged Body (f = 0.32 Hz, Amp = 15 deg, Fwd Speed = 2 knots)

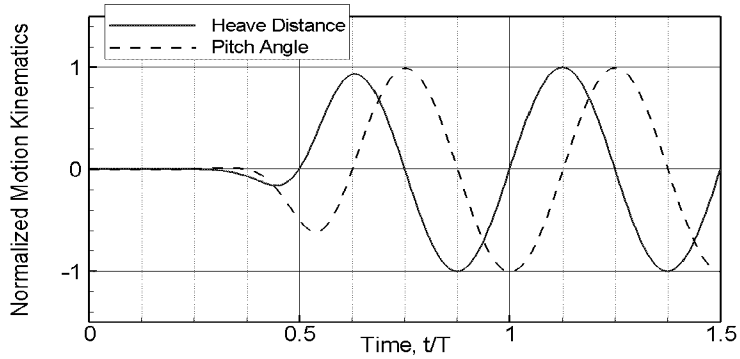

Figure 6. Time History of Pitch and Heave Motions for Unsteady RANS Simulation of Model 5415 using CFDSHIP-IOWA

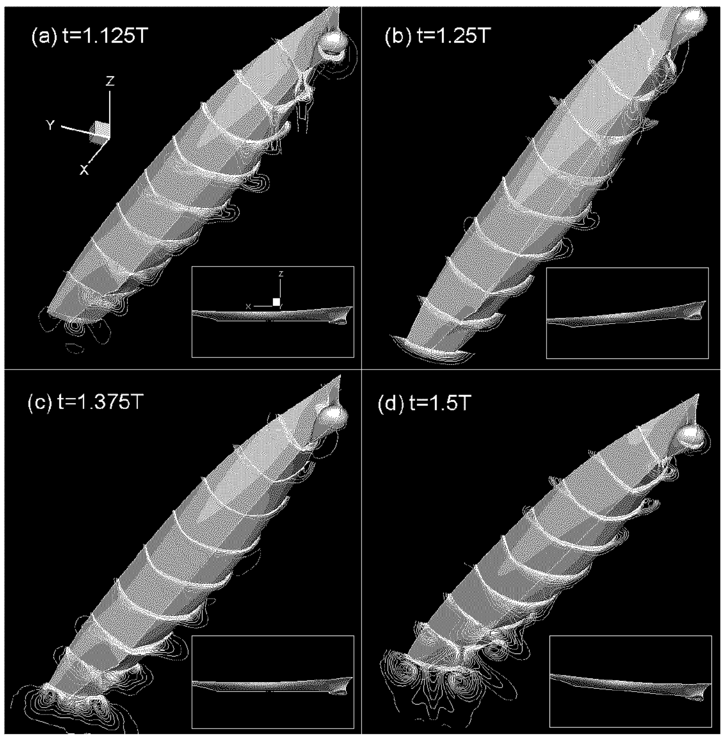

Figure 7. Time Sequence of Axial Velocity Contours for One Period of Prescribed Pitch and Heave Motion from Unsteady RANS Simulation of Model 5415 Using CFDSHIP-IOWA

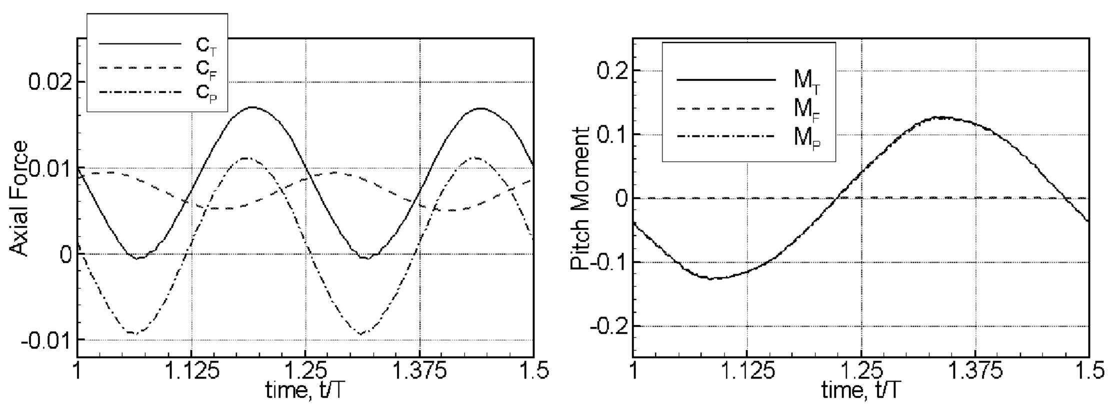

Figure 8. Time History of Axial Force and Pitch Moment of Model 5415 with Prescribed Pitch and Heave Motions from Unsteady RANS Simulation Using CFDSHIP-IOWA

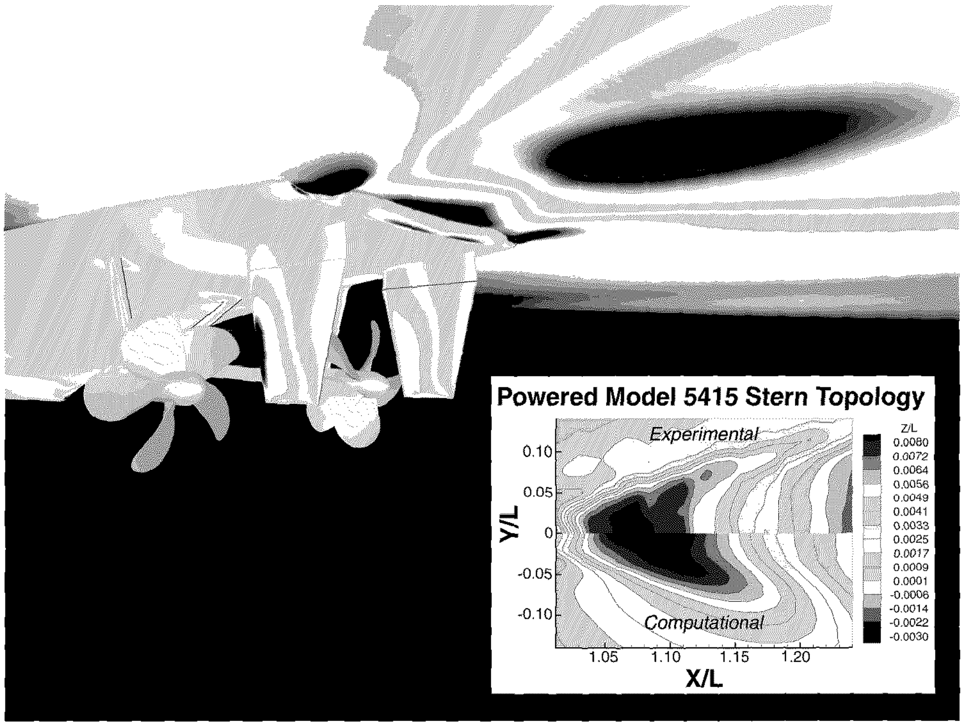

Figure 9. Nonlinear Free Surface Simulation for a Fully Appended Model 5415 Using U^{2}NCLE

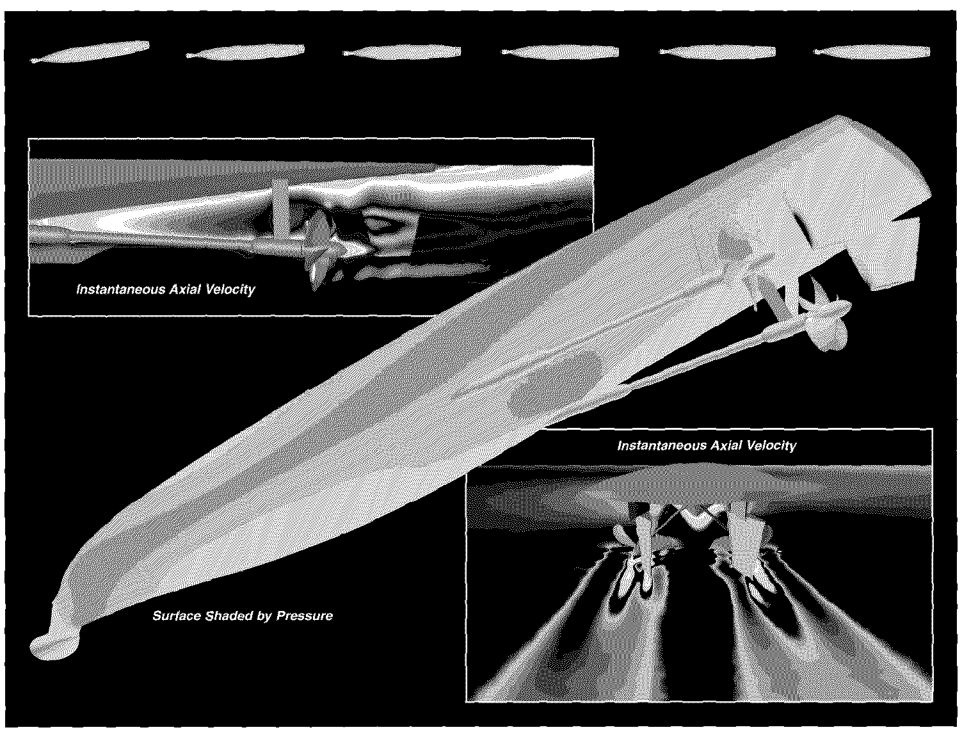

Figure 10. Rudder-Induced Propelled Turning Maneuver with Rigid Free-Surface Condition Using U^{2}NCLE

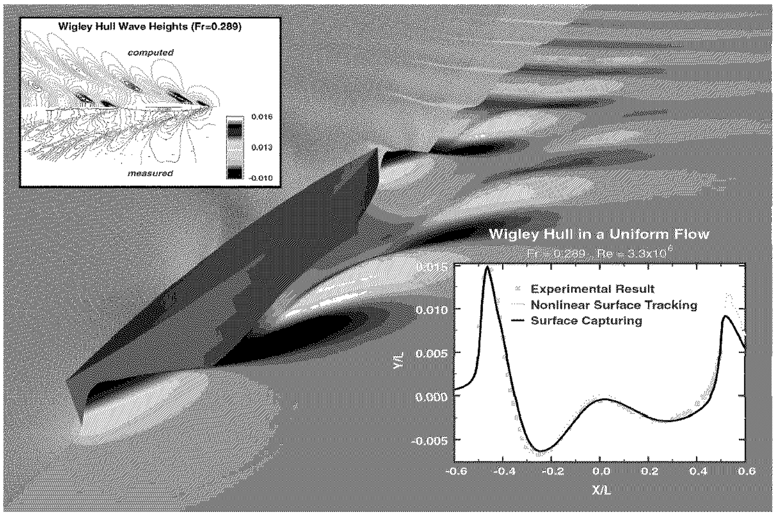

Figure 11. Wave Elevation Using Surface Fitting and Capturing Approaches (Wigley Hull) Using U^{2}NCLE

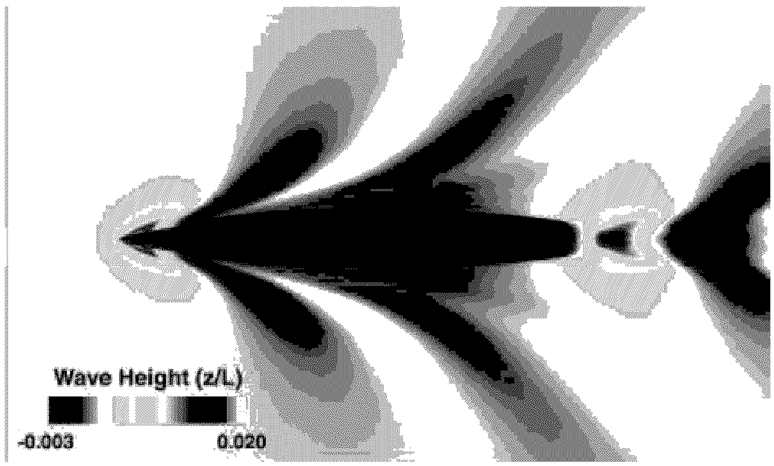

Figure 12. Free-Surface Contours using the Surface Capturing Approach on Model 5415

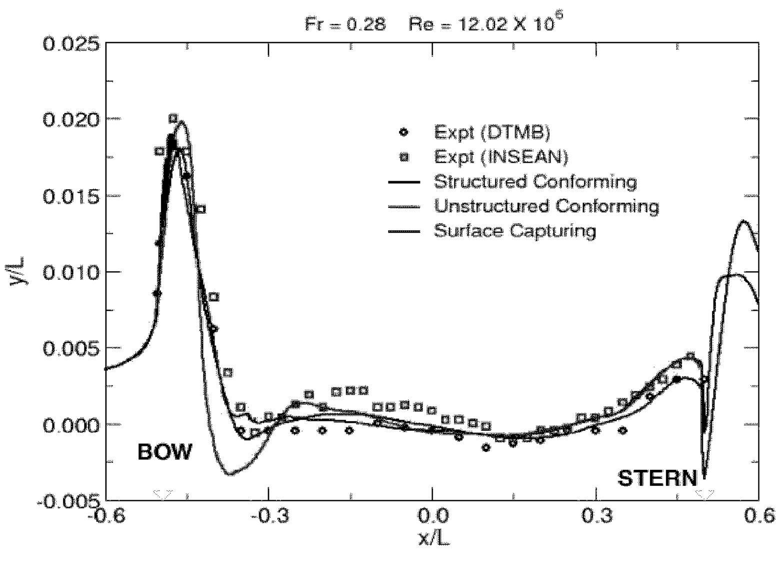

Figure 13. Comparison of Free Surface Elevation on Model 5415 Using U^{2}NCLE

Paper #35
Discussor's name Dr. B. Oskam
Author Dr. K. H. Kim

Q: Your simulation of the fully appended model 5415 is based on the unsteady Reynolds-averaged Navier-Stokes equations with 7 revolutions per second of the propeller. How do you separate the propeller-induced unsteadiness (7 revolutions per second) from the turbulence unsteadiness in, say, the hull boundary layer?

A: Code is based on assumption that the two time scales are sufficiently different.